Cryogenic Avalanche Detectors Based on Gas Electron Mulitipliers

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Outline

Basic part:

- *Motivation: dark matter and solar neutrino detection and PET*
- *GEM operation in gaseous He, Ar and Kr at cryogenic T*
- *Two-phase cryogenic detector in Kr, based on GEMs*

Some details:

secondary effects in two-phase Kr; two-phase Kr + gas;
ionization coefficients; ion-induced signals; photon feedback

Summary

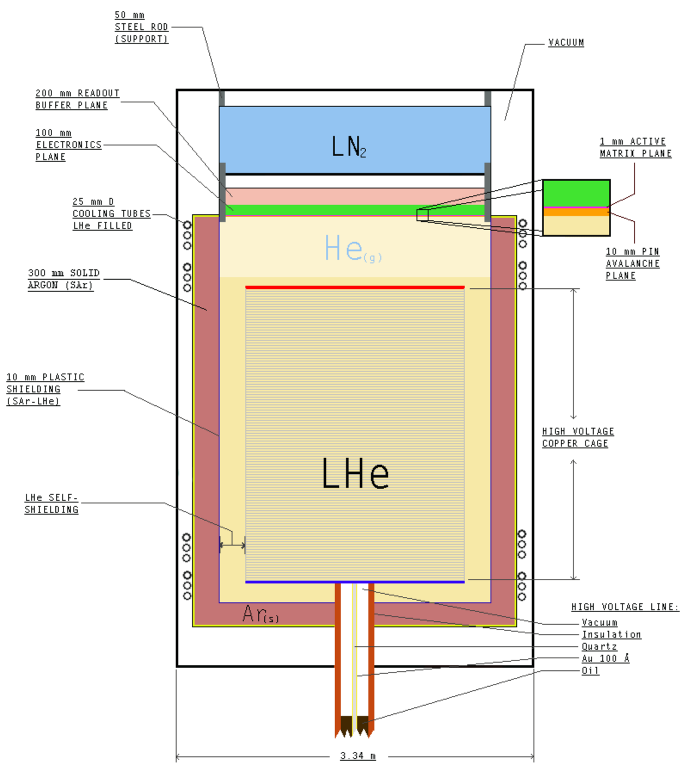
This work is carried out under CRDF grant RP1-2550-NO-03 in collaboration with

J. Dodd, R. Galea, Y. Ju, M. Leltchouk, V. Radeka, P. Rehak, V. Tcherniatine, W. Willis

Nevis Lab & BNL

Two-phase detectors for solar neutrino and dark matter

Two-phase He detector for solar neutrino detection:
Nevis Lab (Columbia Univ) & BNL



Two-phase Xe detectors for WIMP search: ZEPLIN II-IV:
UK Dark Matter Search Collaboration

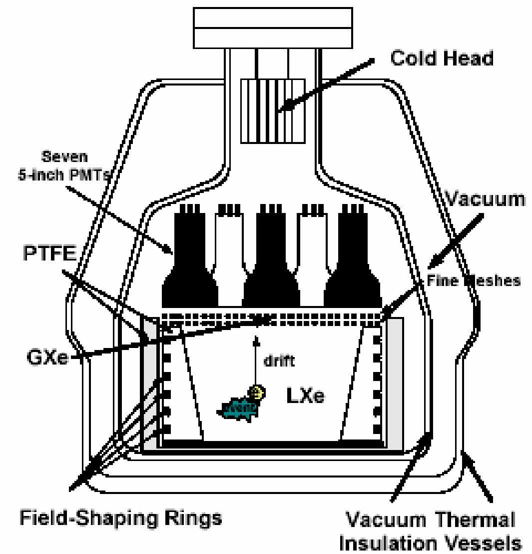
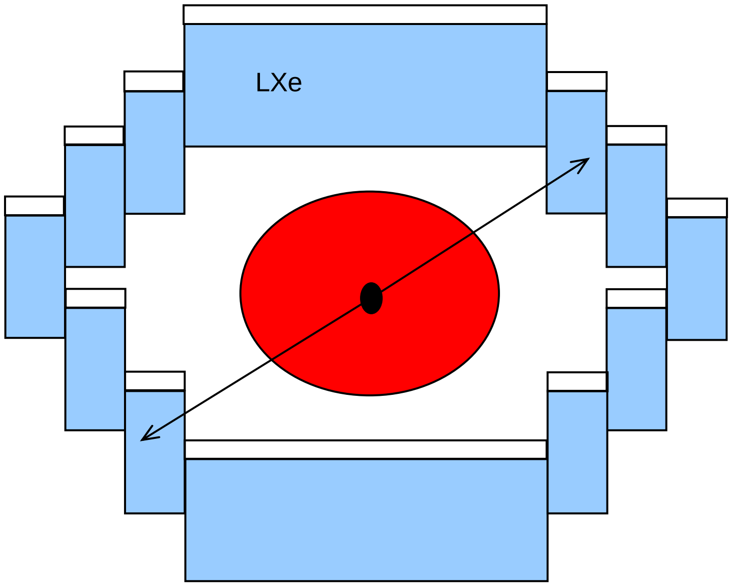


Fig. 1. A schematic diagram of the ZEPLIN II central detector with vacuum thermal insulation vessels, wire meshes, and field-shaping copper wires.

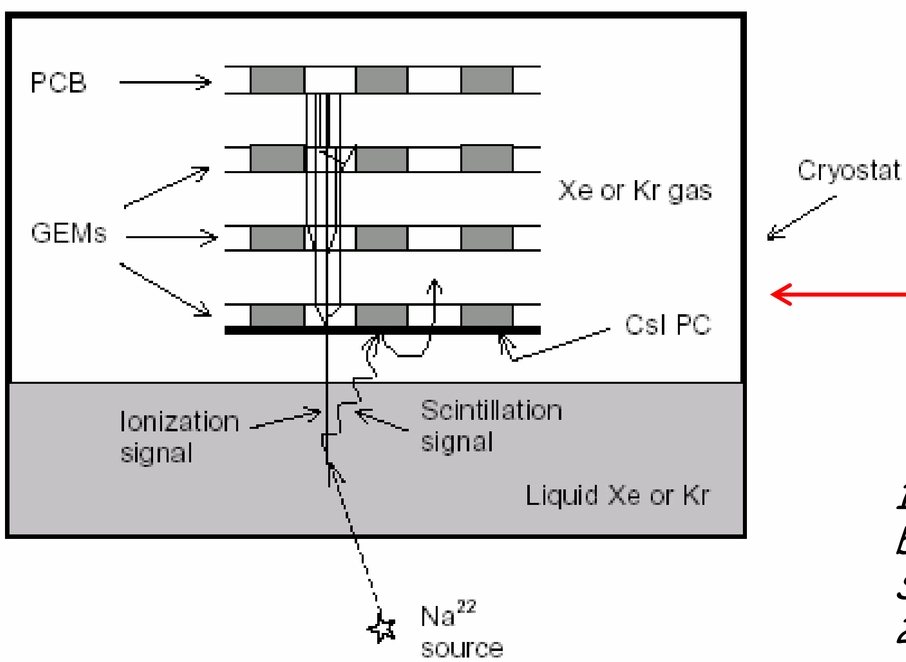
Medical applications: two-phase Xe or Kr detector for PET



- LXe is comparable to NaI (Tl) in atomic number, density and scintillation yield
- LXe price: $10.4/rad. length (2.6 cm) which is comparable with BGO
- LKr price is much lower: $1.4/rad.length (4.6 cm)
- Solving parallax problem

Principle of two-phase cryogenic avalanche detector based on GEMs

- *For solar neutrino and WIMP, primary ionization signal is weak*
  → Signal amplification, namely electron avalanching in pure noble gases at cryogenic temperatures is needed
- *Detection of scintillations in liquid is needed, to provide fast signal coincidences in PET and to reject background in neutrino and WIMP detection*
- *Electron avalanching at low temperatures has a fundamental interest itself.*



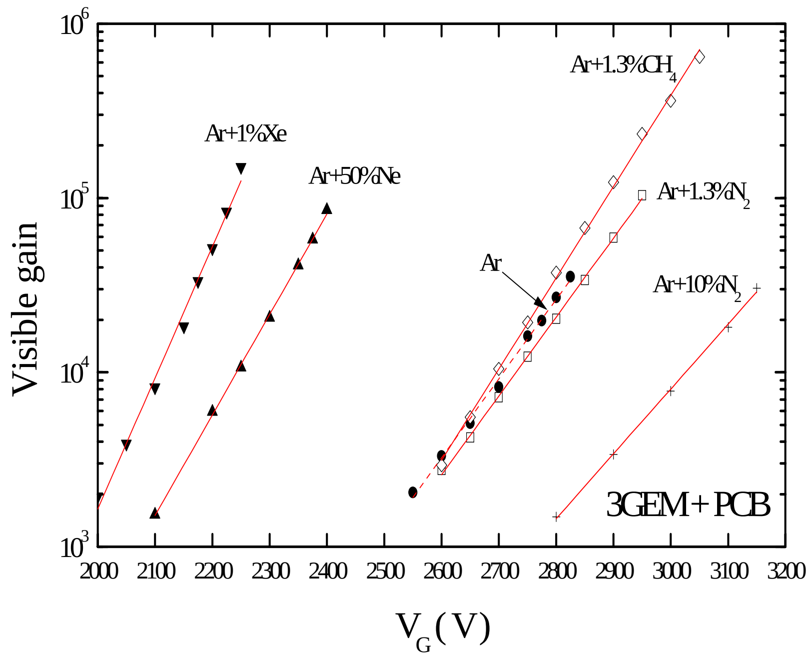
Two-phase (liquid-gas) cryogenic avalanche detector using multi-GEM multiplier, with CsI photocathode on top of GEM

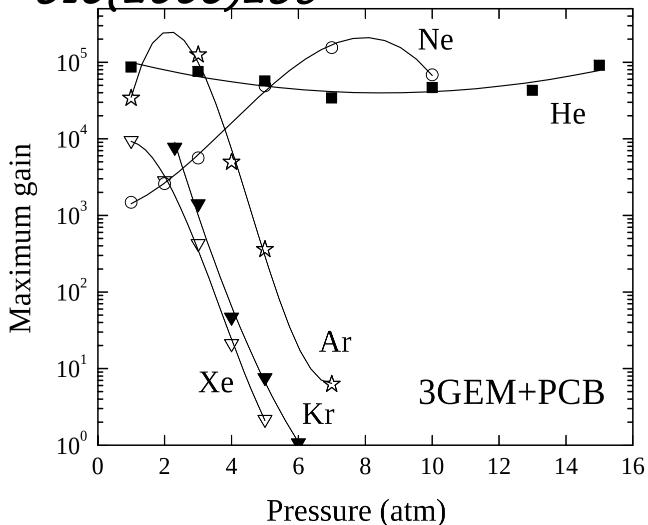
1. First results from cryogenic avalanche detectors based on GEMs, Buzulutskov et al. IEEE Trans. Nucl. Sci. 50(2003)2491; E-print physics/0308010
2. Cryogenic avalanche detectors based on GEMs, Bondar et al., NIM A 524(2004)130.

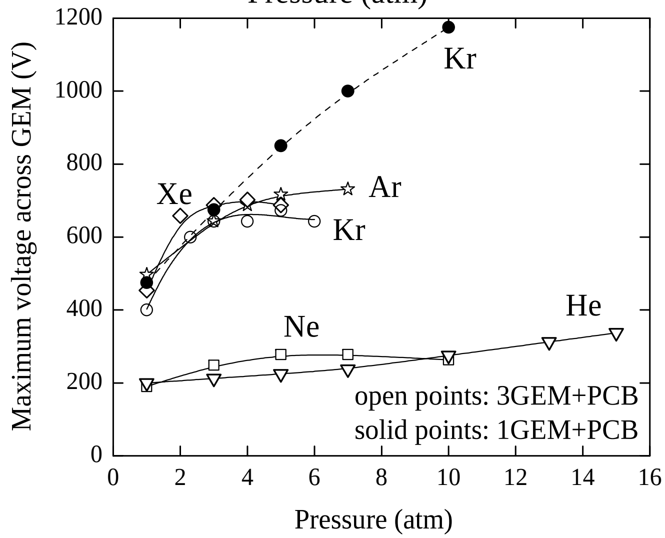
GEM operation in noble gases: previous results

Budker Inst:
NIMA 493(2002)18; 494(2002)148; 513(2003)256

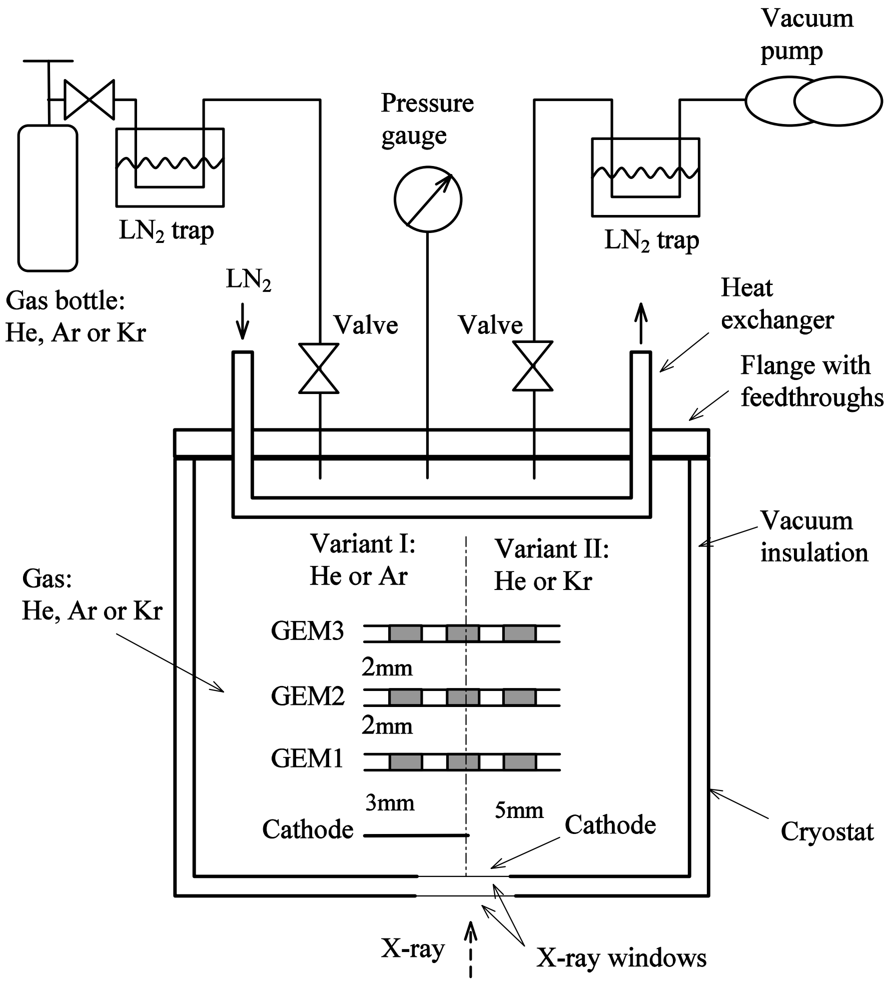
Budker Inst & Weizmann Inst & CERN:
NIMA 443(2000)164



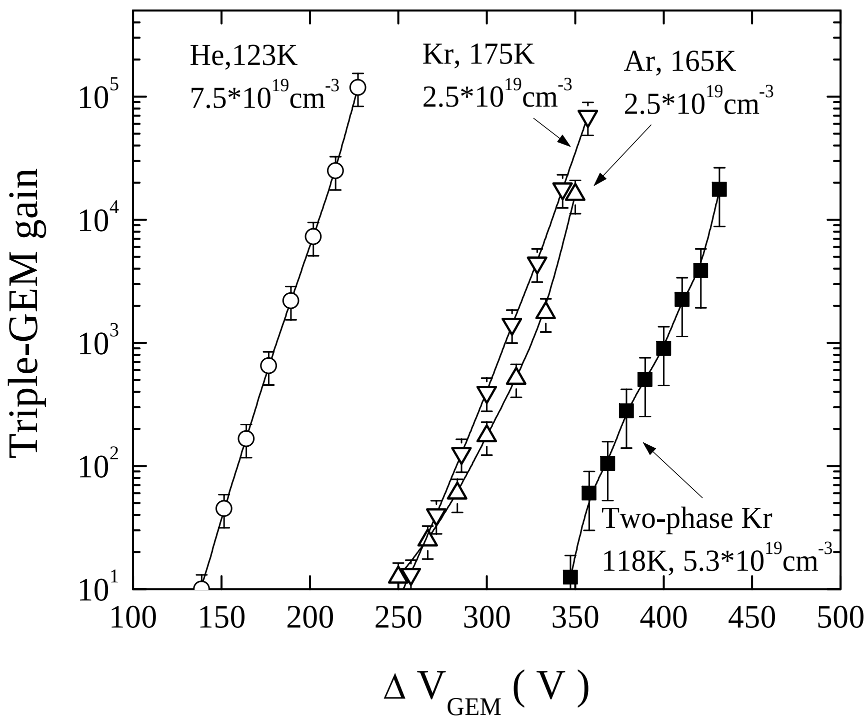




Gaseous cryogenic avalanche detector: experimental setup



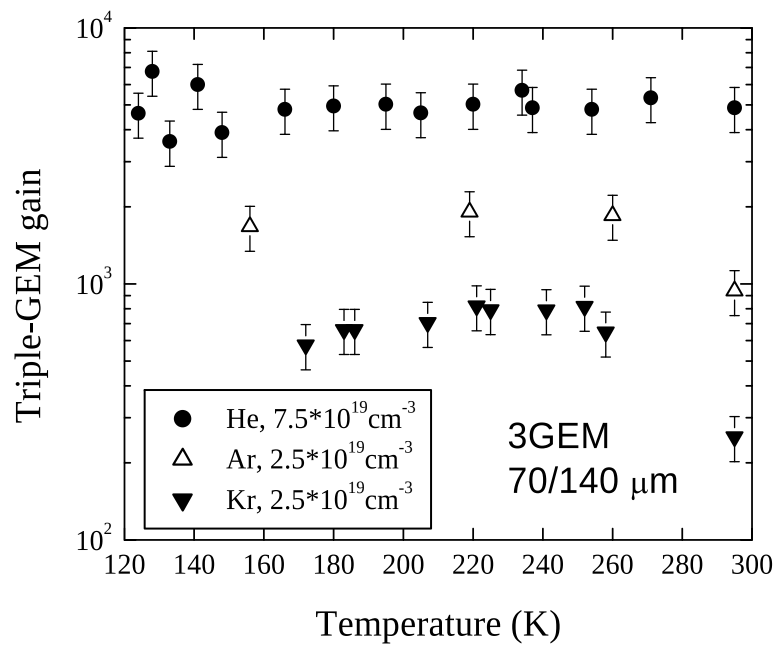
Gain-voltage characteristics at cryogenic T in He, Ar and Kr



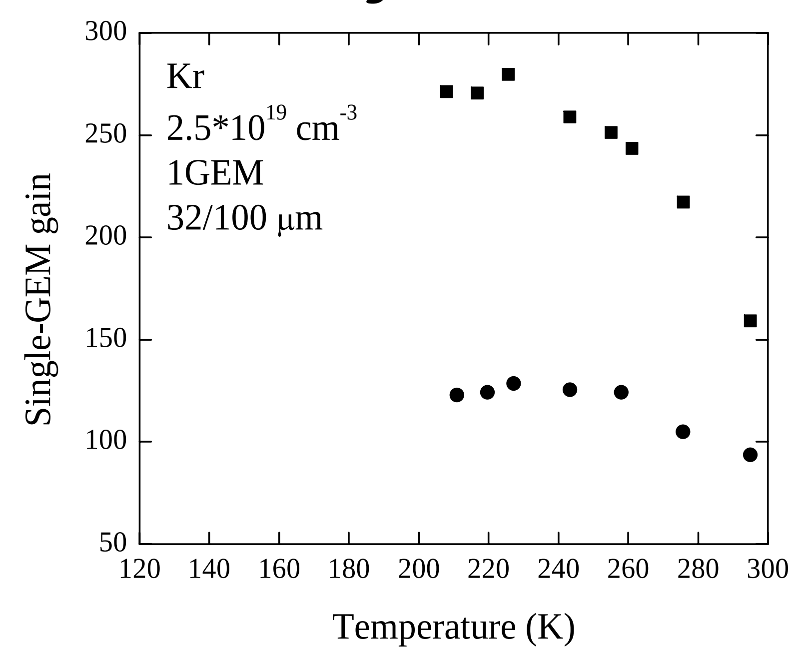
Rather high gains are reached in all the gases studied. The maximum gain exceeds 10^5 and few tens of thousands in He and Ar and Kr, respectively.

Temperature dependence of gain at constant voltage and constant gas density

Triple-GEM in He, Ar, Kr



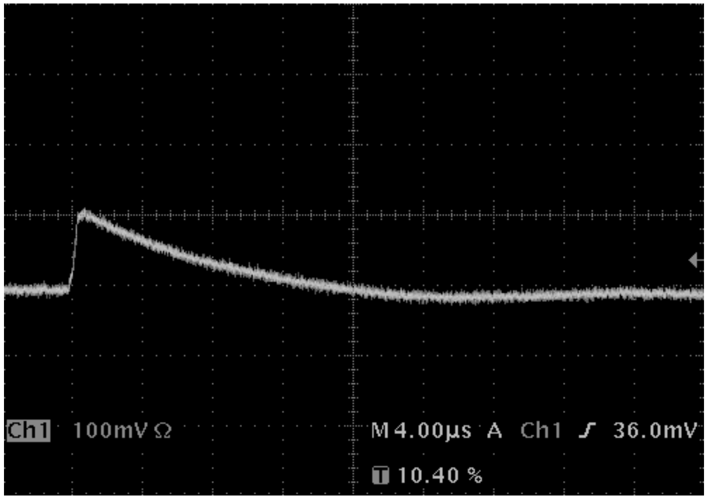
Single-GEM in Kr

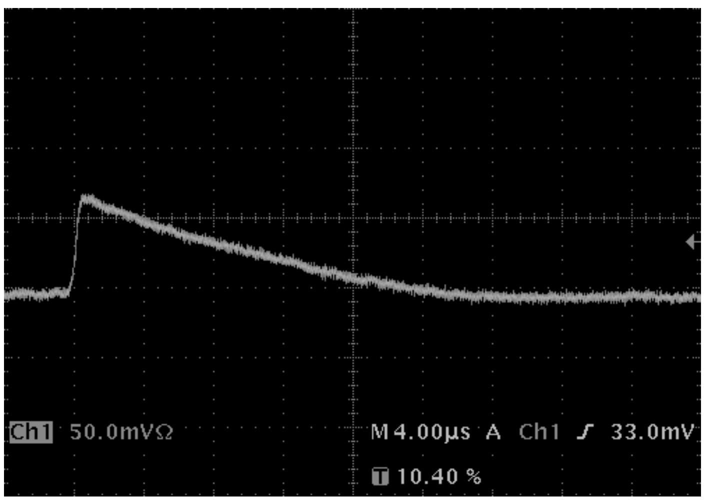


- In He, gain is independent of temperature, ruling out effect of organic impurities on avalanche mechanism.

- In Ar and Kr, gain increases by a factor of 1.5-5, in 3 GEM, and 1.1-1.8, in 1GEM, when decreasing temperature → modification of avalanche mechanism?

He: anode signals at cryogenic T, induced by X-rays



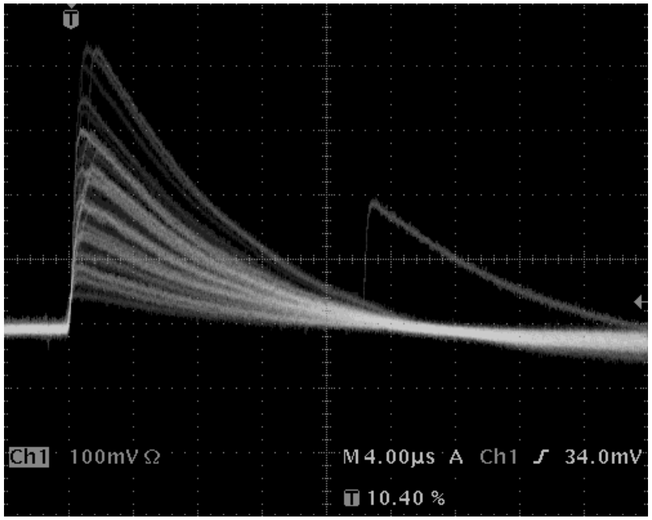


We do not observe any unusual properties in the shape of anode pulses, induced just by cryogenic temperatures.

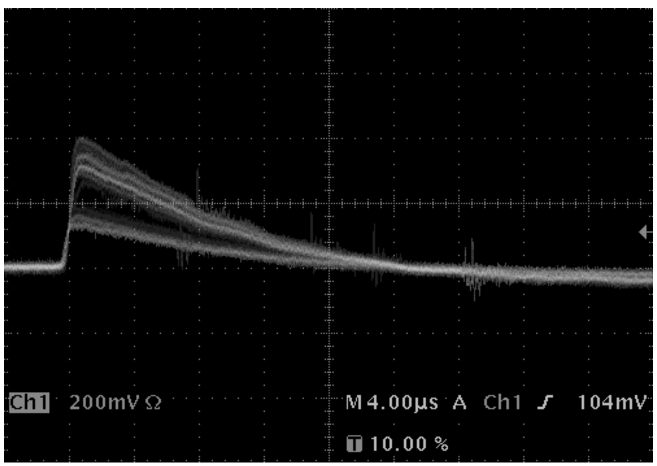
T = 295 K
*p = 3 atm , N=7.5*10^{19} cm^{-3}*
Gain~6000
Stainless steel cathode

T = 124 K
*p = 1.26 atm , N=7.5*10^{19} cm^{-3}*
Gain~6000
Stainless steel cathode

He and Kr: anode signals at cryogenic T, at high gains

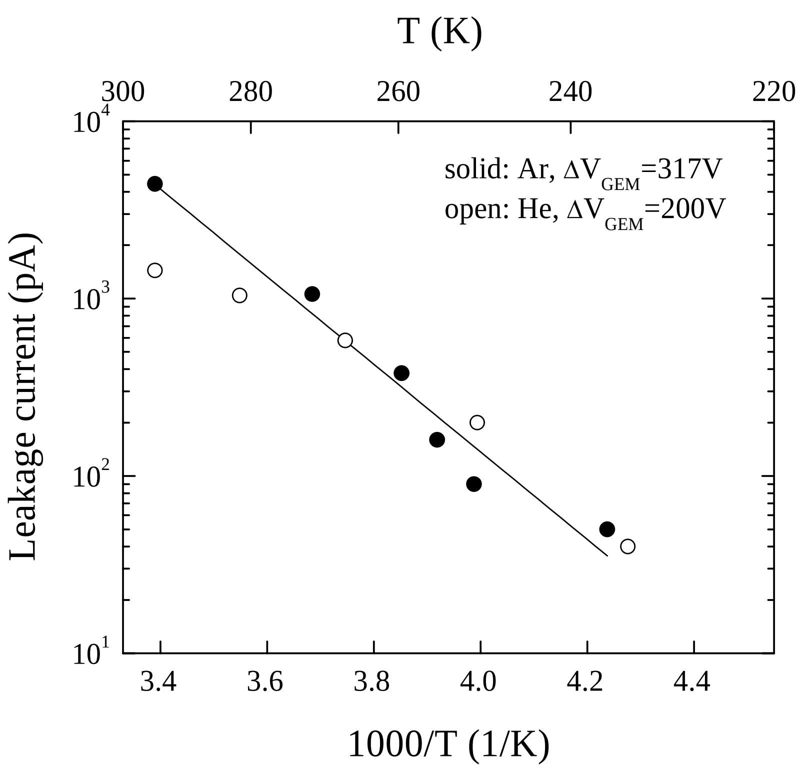


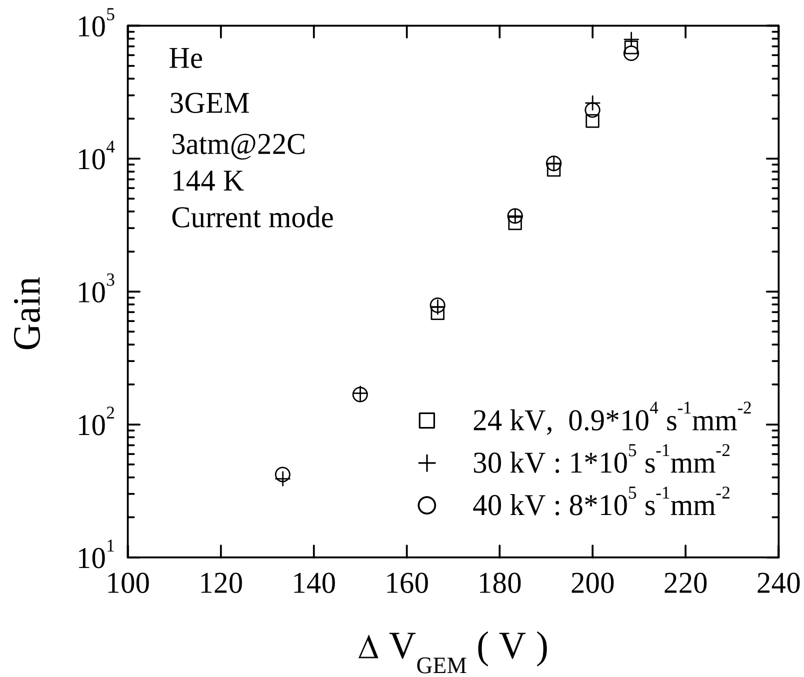
He, T = 125 K
$N=7.5*10^{19}$ cm^{-3}
Gain~25000
Stainless steel cathode
X-ray tube with Re target



Kr, T = 180 K
$N=2.5*10^{19}$ cm^{-3}
Gain~18000
Stainless steel cathode
X-ray tube with Mo target

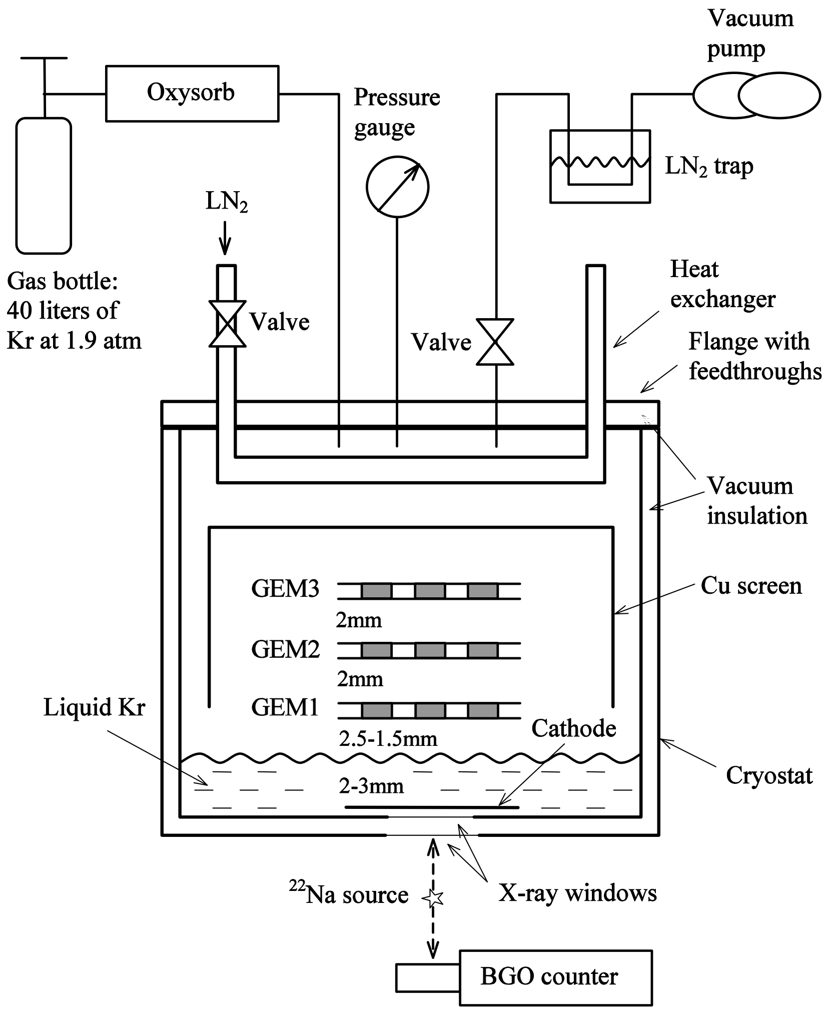
No charging-up effects at cryogenic T





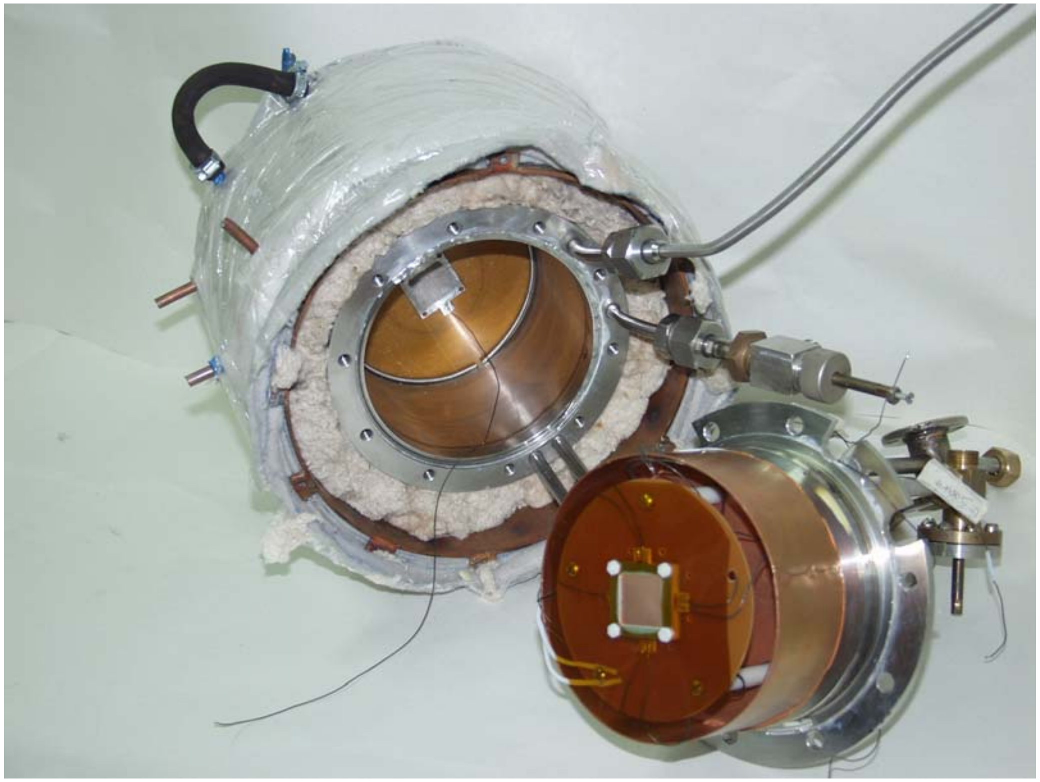
$\sigma \sim exp\,(-E_A / kT)$

Two-phase cryogenic avalanche detector: experimental setup

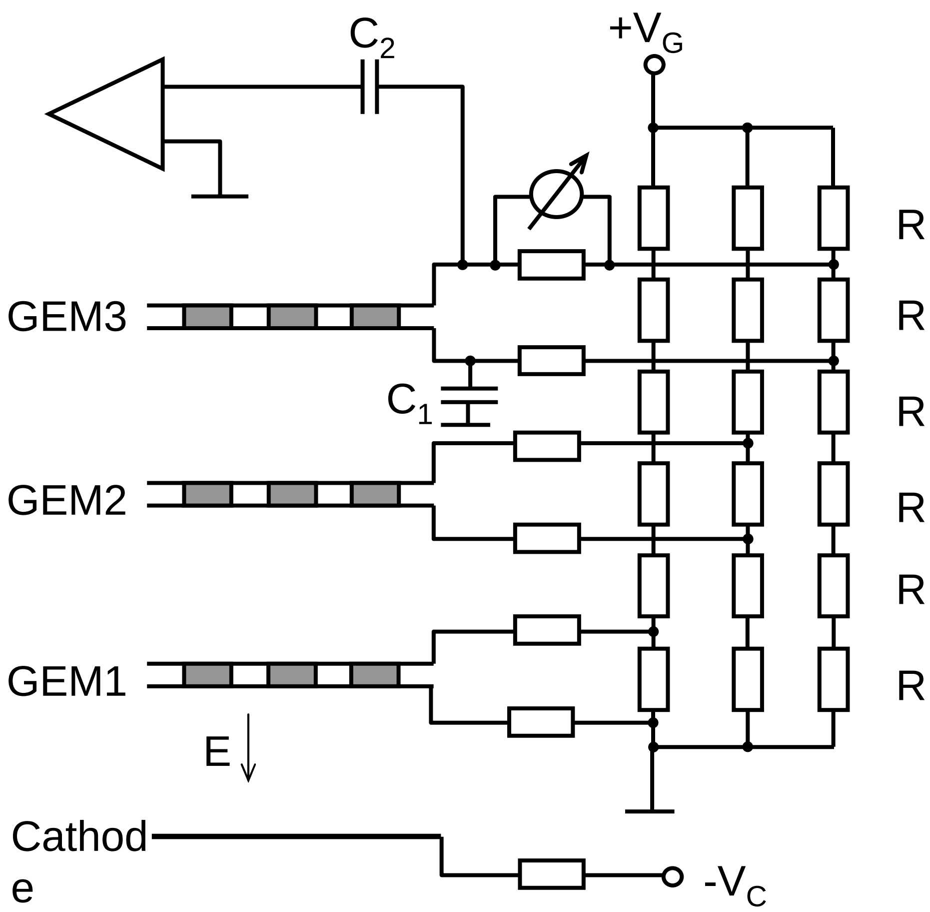


- Liquefying starts when Kr pressure drops below 1.5 atm
- Strong p-T dependence in two-phase mode → monitoring pressure to measure temperature

Two-phase cryogenic avalanche detector: experimental setup

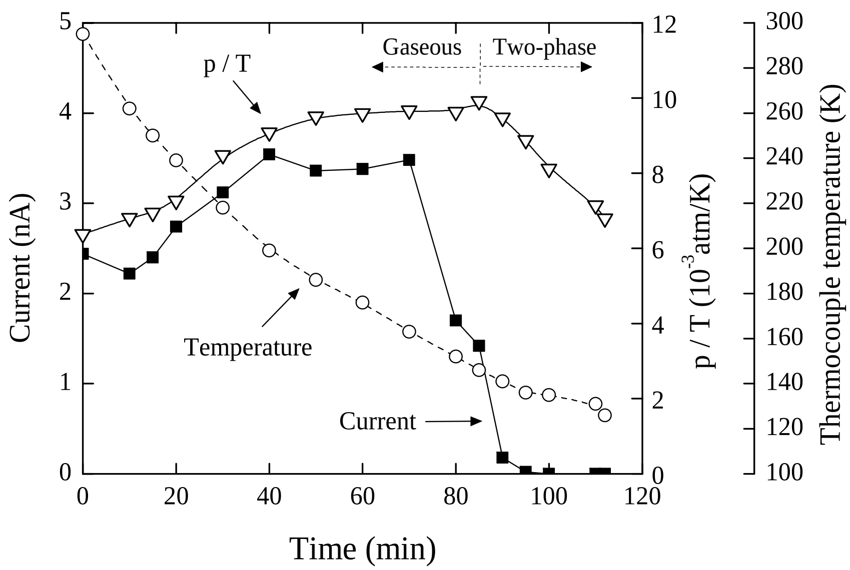


High-voltage divider and readout

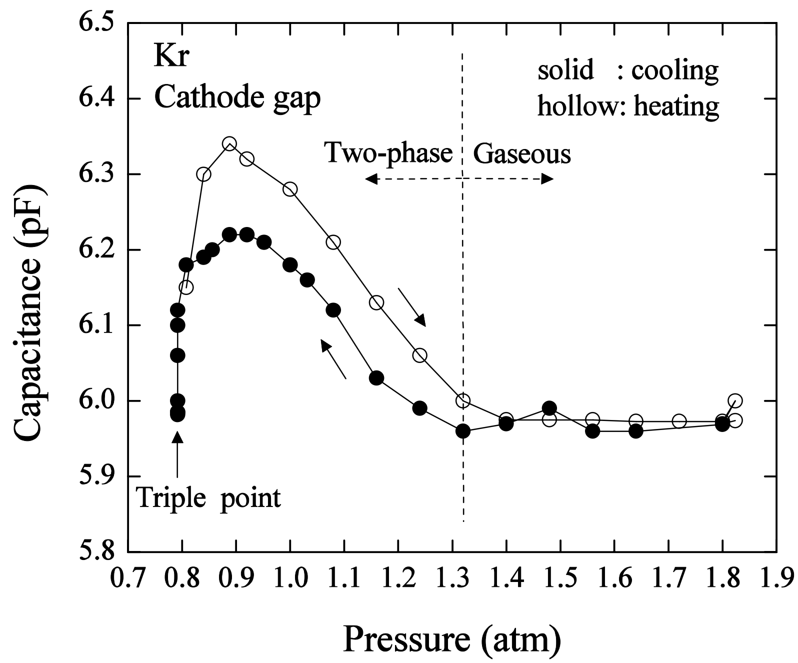


- Divider: three identical circuits connected *in parallel*, *each GEM being connected to one of them:*
- Protection against discharges induced by ion feedback between GEMs: if even one GEM breaks-down, electrical potentials on others do not increase.

Two-phase Kr: formation of liquid phase



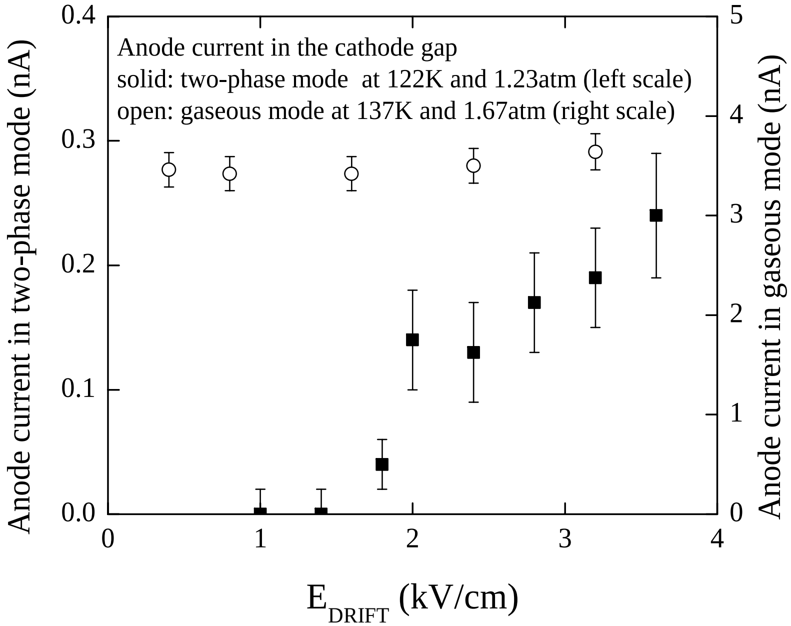
Anode current in the cathode gap, T and p/T as a function of time during cooling cycle



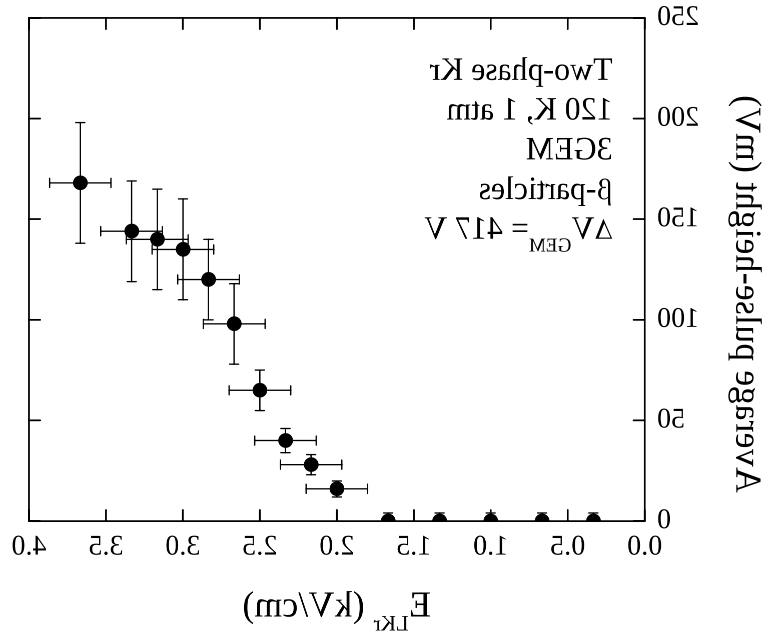
Cathode-GEM1 capacitance as a function of pressure during cooling/heating cycles

- *Liquefying starts when Kr pressure drops below 1.5 atm*
- *Strong p-T dependence in two-phase mode*

Two-phase Kr:
electron emission from liquid into gas



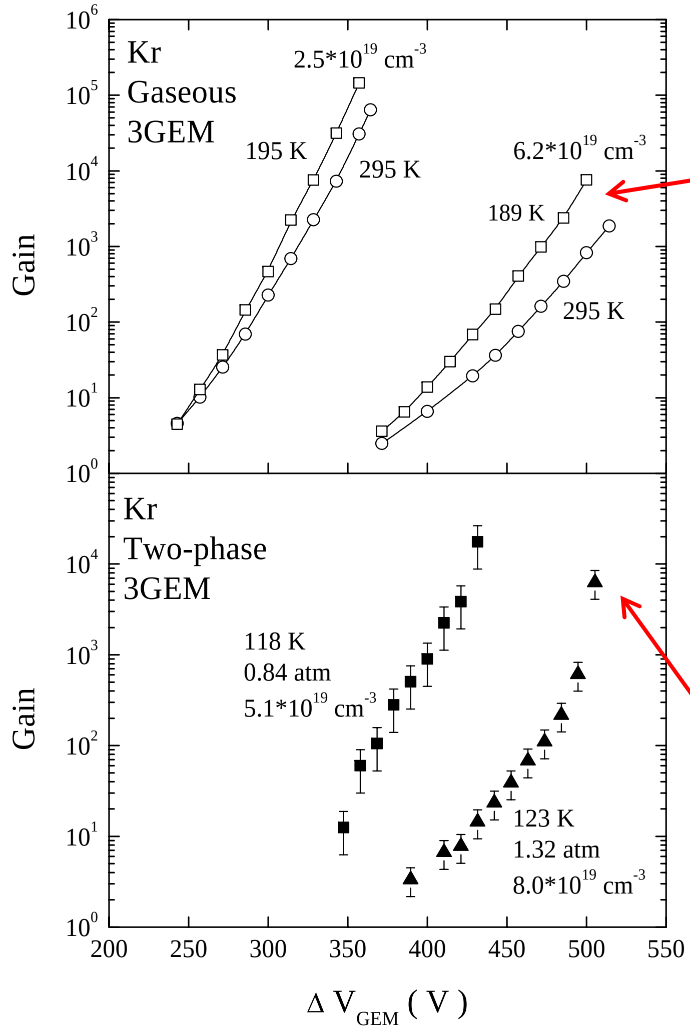
Anode current recorded in the cathode gap as a function of the electric field, induced by X-rays



Anode pulse-height as a function of the electric field in liquid Kr, induced by beta-particles (gain@3.3kV=250)

- *Electron emission from liquid into gas phase has threshold behavior*
- *Critical electric field ≥ 1.5 kV/cm*

Two-phase Kr:
gain-voltage characteristics



Gaseous Kr:

Change of slope at low T indicates that the avalanche mechanism is modified?

Two-phase Kr:

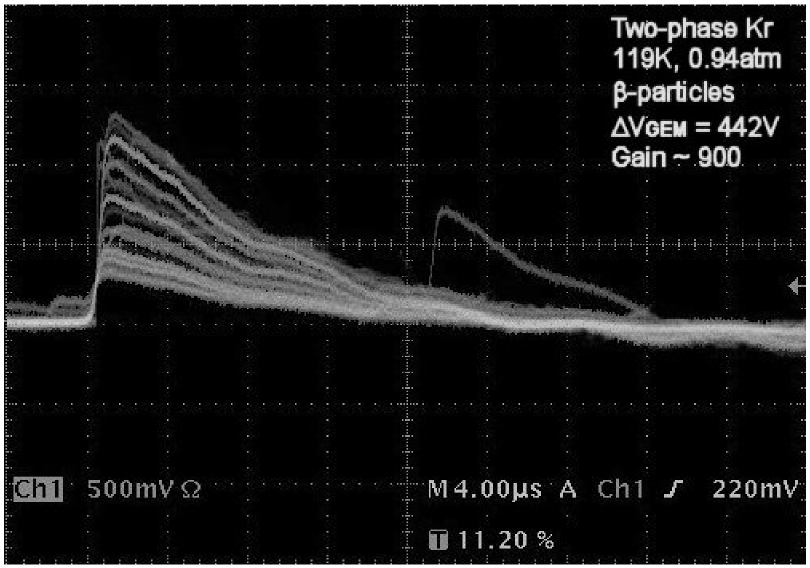
Electron avalanching in saturated vapor does not differ from that of normal gas in general:

- Gain and voltages are similar to gaseous mode at equal gas densities

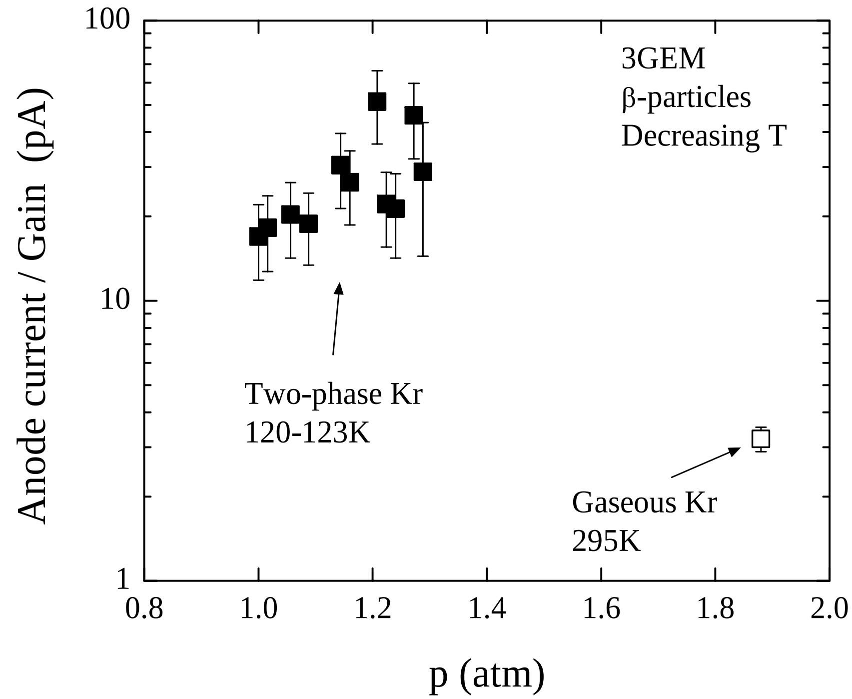
- Secondary processes at high gains are more pronounced

Two-phase Kr:
anode signals induced by β-particles from ^{90}Sr

Pulsed mode

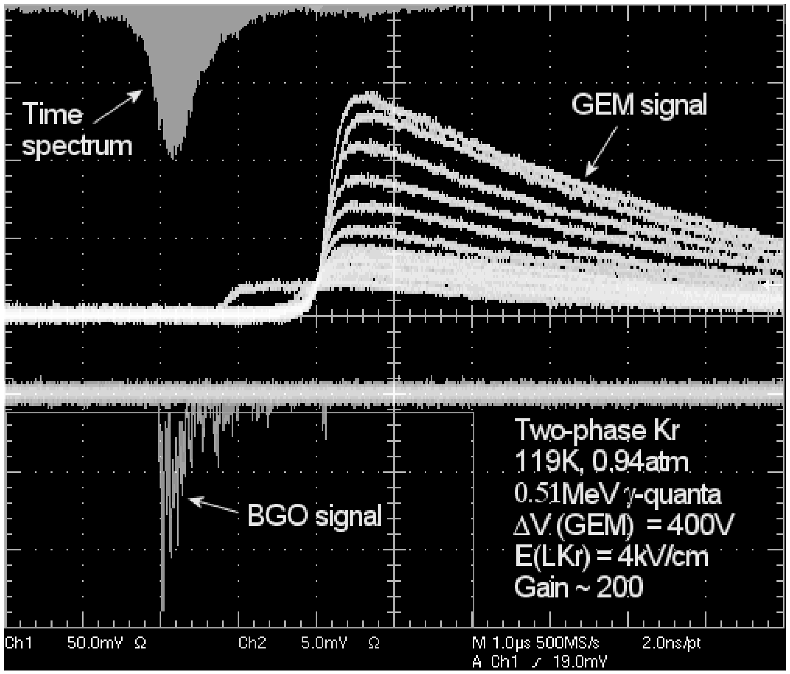


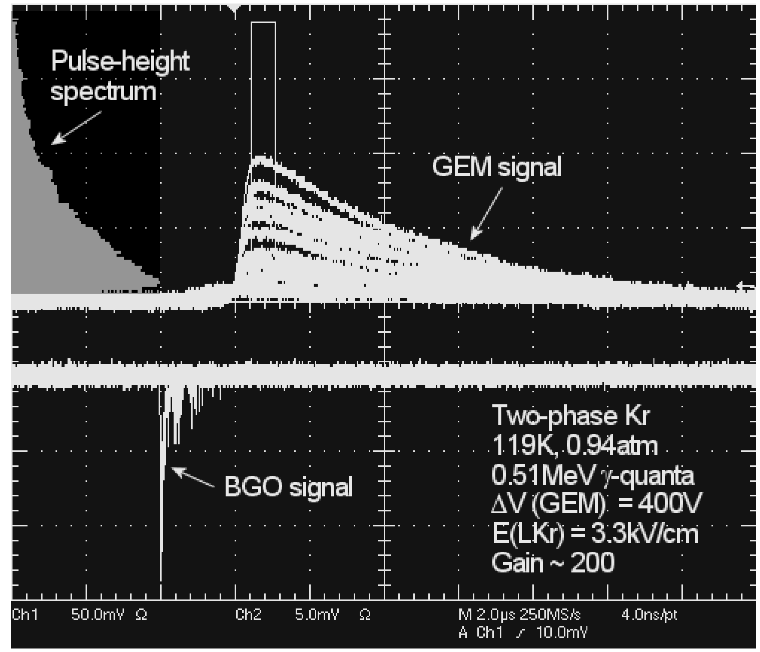
Current mode



The signal in two-phase mode is larger than in gaseous mode, because the energy deposited by β-particle in the liquid is much larger than in the gas

Two-phase Kr: towards PET applications. Anode signals induced by 0.51 MeV γ-quanta from ^{22}Na in coincidences with BGO counter

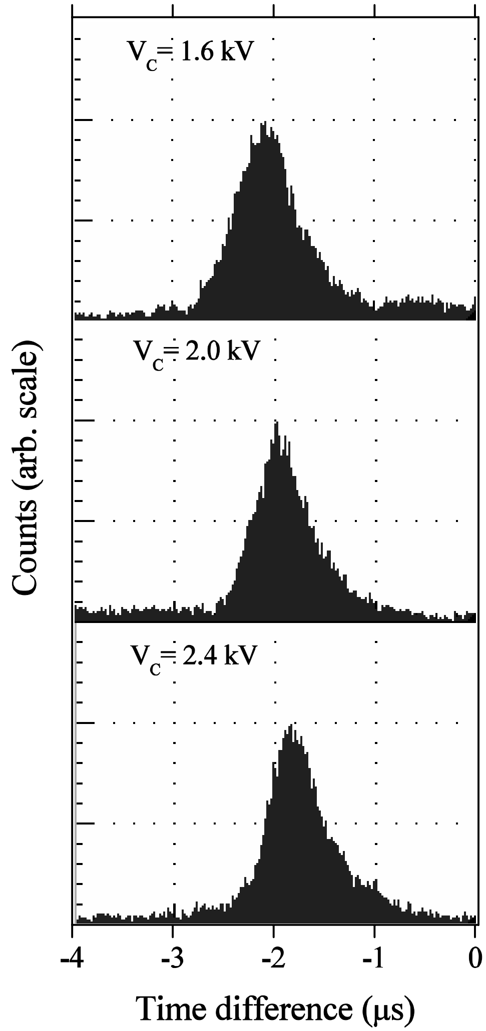


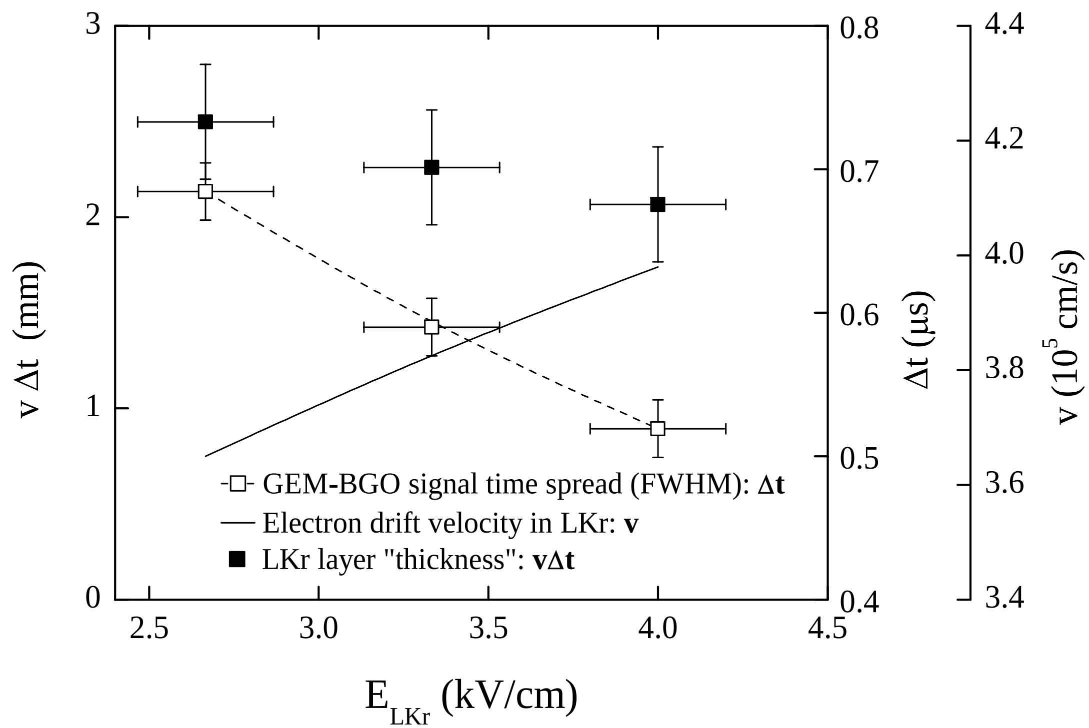


- Triggered by GEM signal
- Almost no background
- GEM-BGO signal delay is t~2 μs: corresponds to electron drift in liquid and gaseous Kr in the gap and between GEMs

- No peak in pulse-height spectrum from 0.51 MeV gammas, due to domination of Compton scattering in LKr.

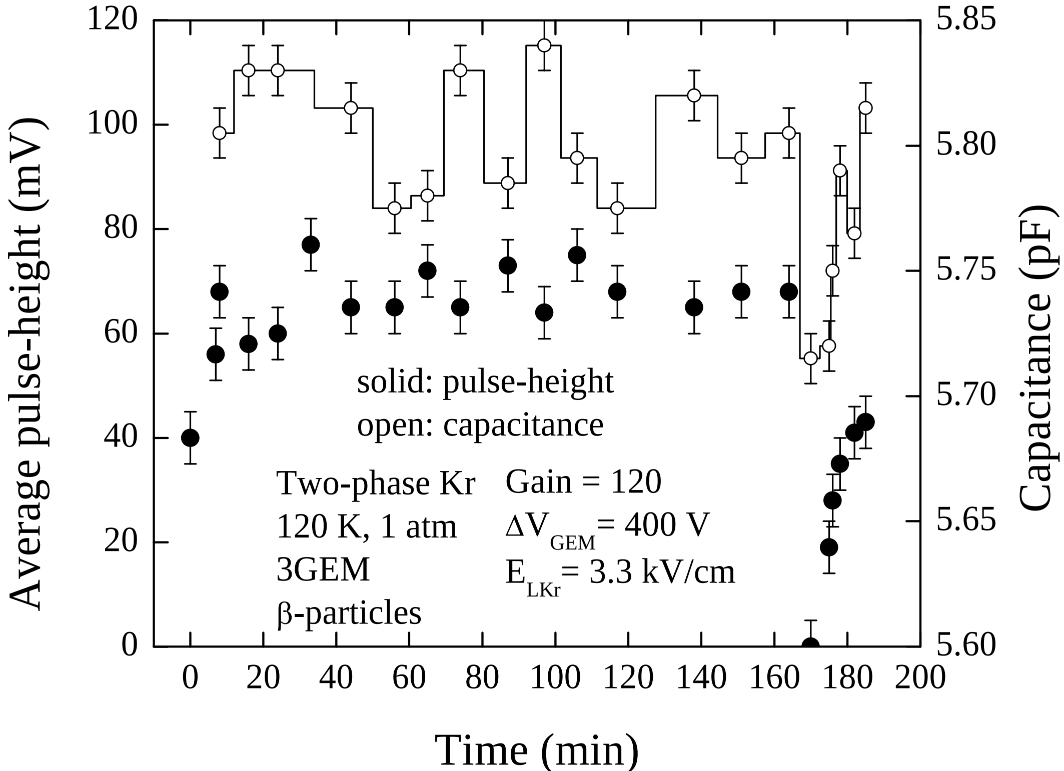
Two-phase Kr:
analysis of GEM-BGO signal time spectra





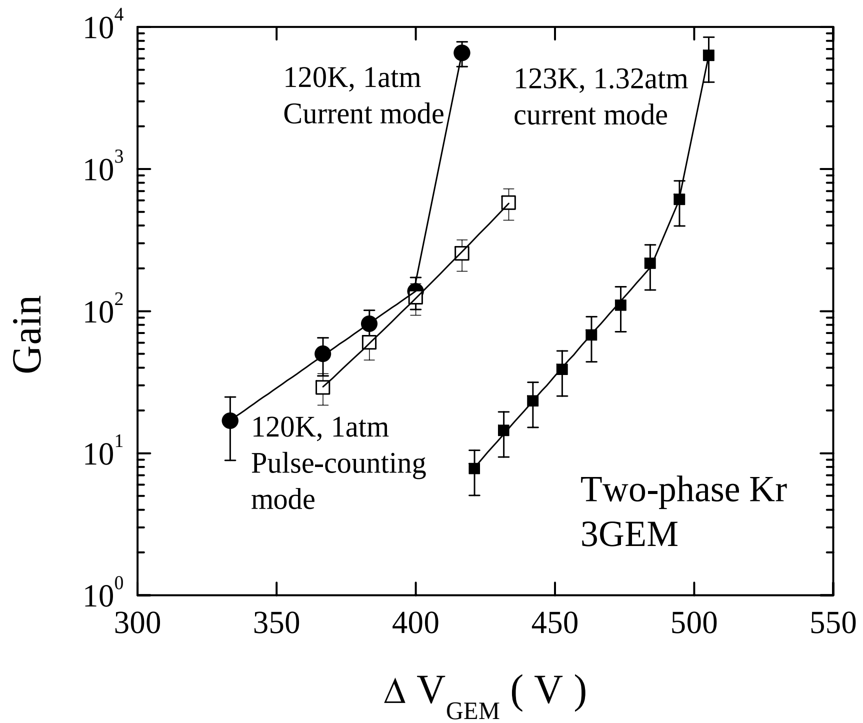
- *Left edge of time histogram is defined mostly by LKr layer thickness*
- *Fitting left edge by Gauss: getting time spread Δt*
- *Δt and t decreases with E due to increase of v*
- *Estimating LKr layer thickness: $\Delta x = v \Delta t$*

Two-phase Kr: stability of operation



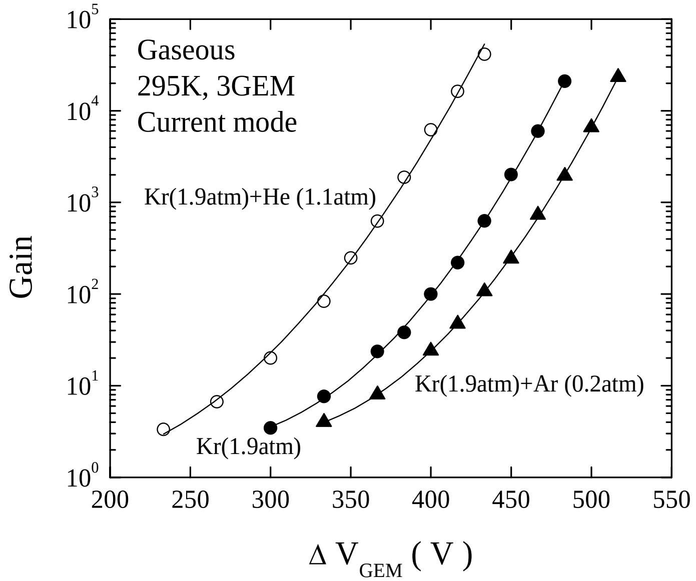
- Relatively stable operation for 3 hours was observed, confirming possibility for stable GEM operation in avalanche mode in saturated vapor
- Signal disappearance is correlated to drop of cathode-GEM1 capacitance, indicating disappearance of the liquid phase, and is due to not enough temperature stability of the cryostat

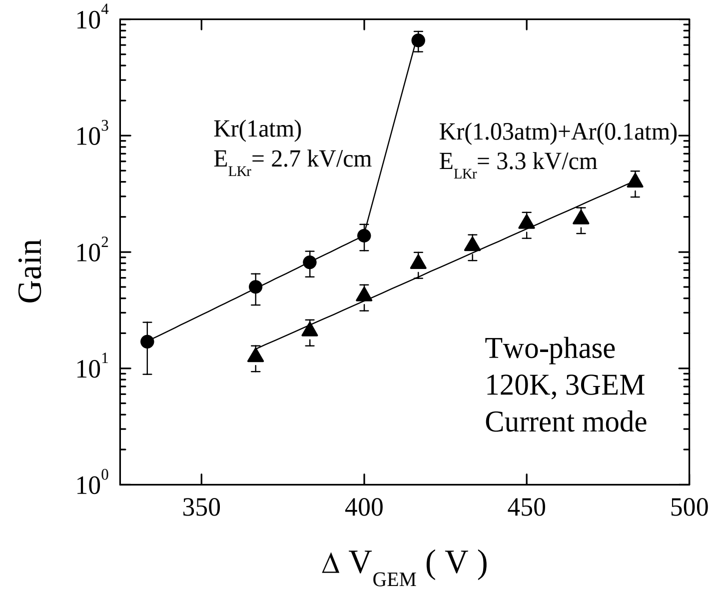
Two-phase Kr:
secondary effects and maximum gain



- In pulse-counting mode, the maximum gain does not exceed 1000.
- In current mode, secondary effects arise at higher gains. They are not observed in pulse-counting mode. Most probably they are induced by ion backflow, which at high fluxes might result in
a) ion feedback between GEMs (enhanced in saturated vapor?)
b) charging-up of kapton in GEM holes (enhanced in saturated vapor?)
c) charging-up at phase interface (what happens to electrons not emitted from liquid?).
- Secondary effects might also be dependent on liquid surface state (surface waves, boiling) and electric field.
- Ways to increase the gain and suppress secondary effects should be looked for.

Two-phase Kr + Ar or He





- In gaseous state: successful operation in Kr+He and Kr+Ar mixtures

- In two-phase state: the basic idea is to suppress boiling and ion feedback.
- However, in Kr+He cooling down to two-phase state was not possible
- In Kr+Ar, cooling down to two-phase state was possible at only small (~0.1atm) Ar content
- In Kr+Ar, secondary effects seems to be reduced, though the maximum gain did not increase.

Estimation of ionization coefficients in dense noble gases using GEMs with narrow holes

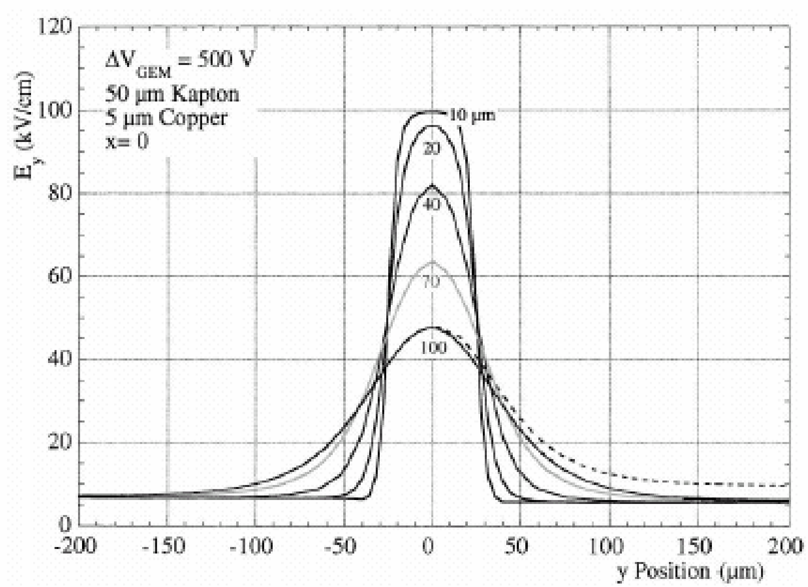


Fig. 10. Electric field computed along a line through the center of the holes, for different hole diameters.

Parallel-plate approach:
works well for hole diameter below 40 μm:

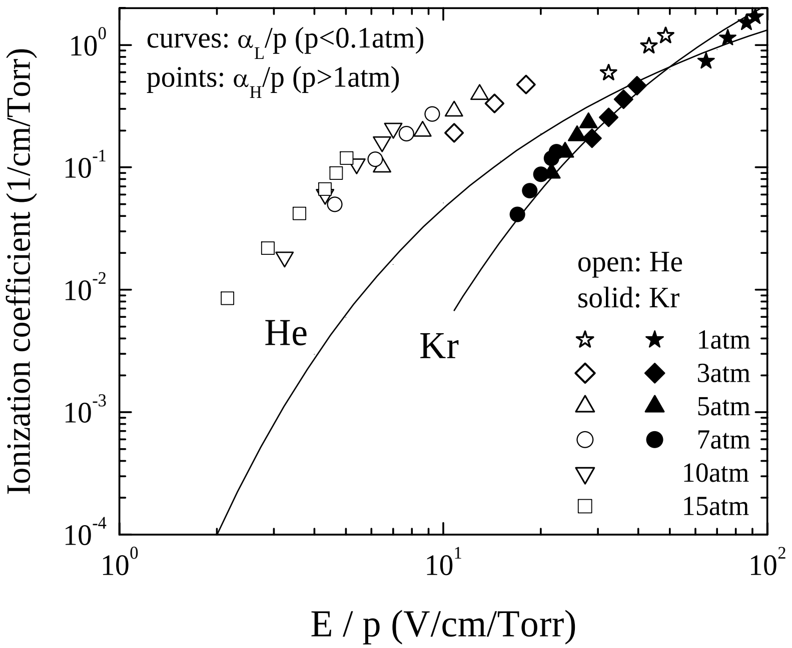
1. Gain of 1GEM configuration:
$G = \exp(a\,d)$.

2. Ionization (Townsend) coefficient:
$a / p = \ln G / (p\,d)$.

3. Electric field: computed value is taken in the center of the hole:
$E = 80$ kV/cm at ΔV_{GEM}=500V.

See: Physics of multi-GEM structures, Buzulutskov, NIM A 494(2002)148.

Ionization coefficients: high pressure versus low pressure

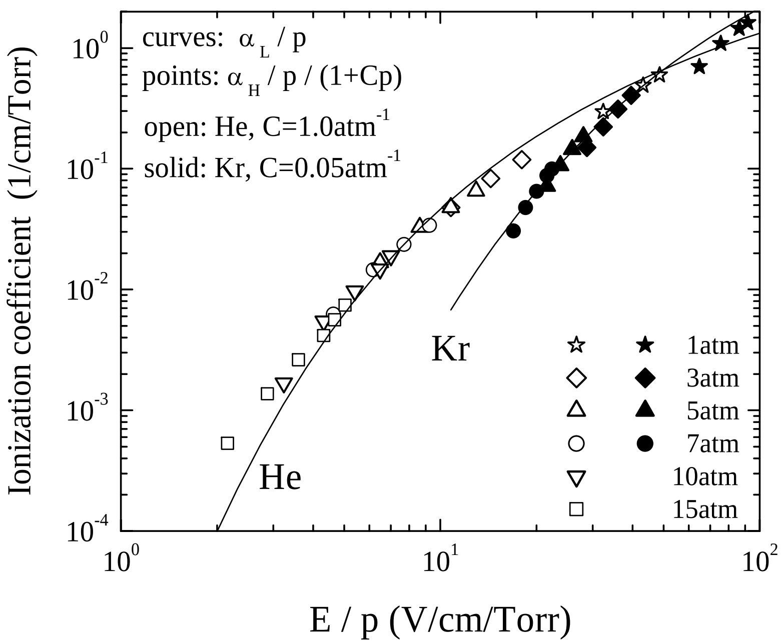


Using 1GEM (40/100μm) data

1. In He and Ne, ionization coefficients are considerably larger at high pressures than at low pressures.
2. In He and Ne: strong violation of E/p scaling.
3. In Ar, Kr and Xe: relatively good agreement between high and low pressure.

$A + e \rightarrow A^+ + 2e$	Impact ionization: ~p
$A + e \rightarrow A^* + e$	Excitation
$A + A^* \rightarrow A^+_2 + e$	Associative ionization: ~p^2
$A^* \rightarrow A + h\upsilon$	Deexcitation

Ionization coefficients: accounting for associative ionization



$$\alpha_t = \alpha_i + \alpha_a$$

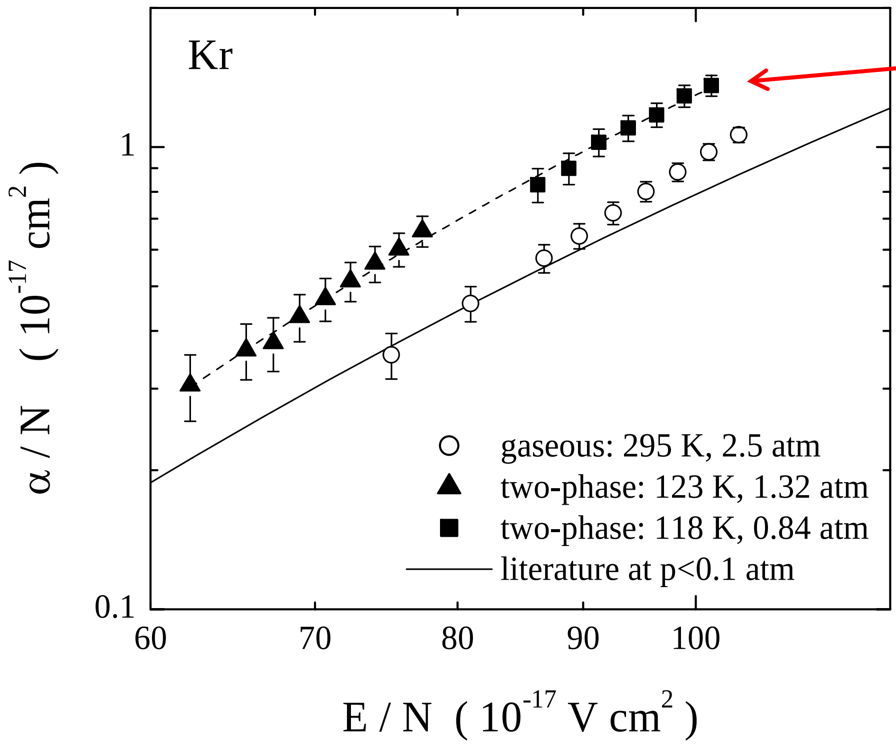
$$\alpha_a / \alpha_i \sim p$$

$$\frac{\alpha_t}{p}(\tfrac{E}{p}, p) \approx [1 + const \cdot p]\frac{\alpha_i}{p}(\tfrac{E}{p})$$

$$\frac{\alpha_H}{p(1+Cp)} \approx \frac{\alpha_L}{p}$$

Parameter C describes the contribution of associative ionization:
$C \sim 1.0$ atm^{-1} for He and Ne;
$C < 0.1$ atm^{-1} for Ar, Kr and Xe.

Two-phase Kr: ionization coefficients

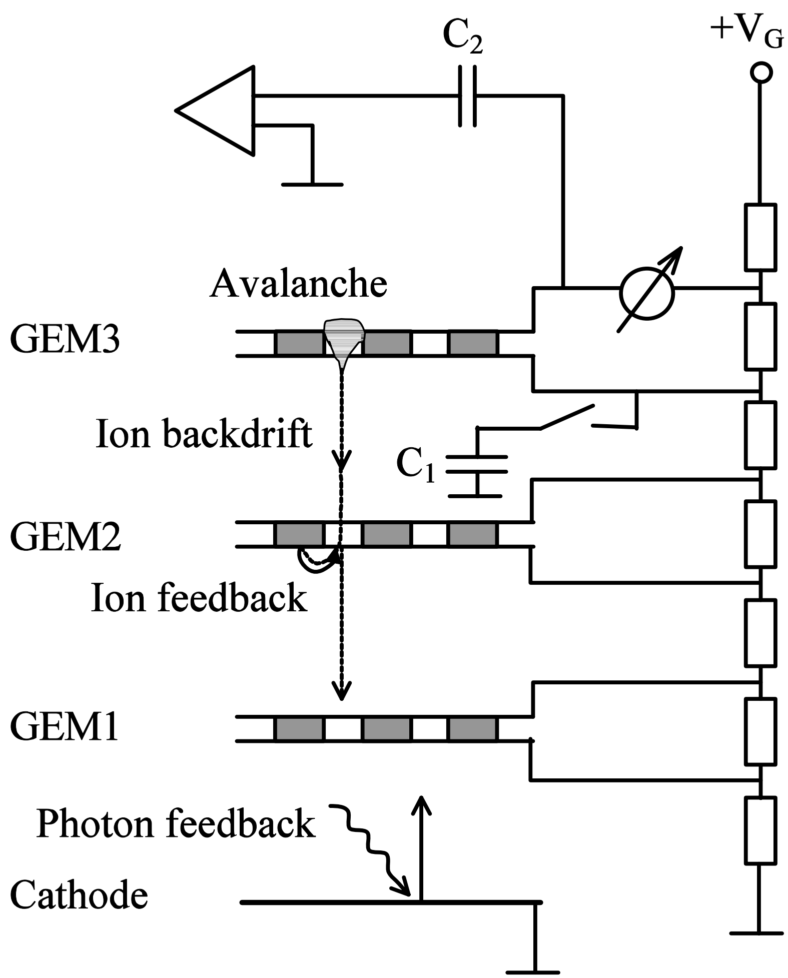


Important observations:

- Scaling of ionization coefficients obtained at different pressures in two-phase mode

- Larger ionization coefficients at lower T → modification of avalanche mechanism?

Gaseous mode:
ion backdrift, ion feedback and photon feedback effects

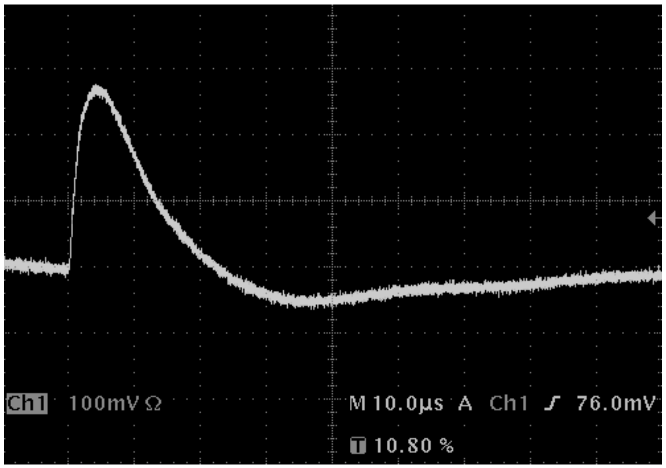


- When C1 capacitor is off, the tail of anode pulse becomes substantially longer due to ion backdrift-induced signal: its width corresponds to ion drift time between GEMs

- This would allow to estimate ion mobility at high densities and low T.

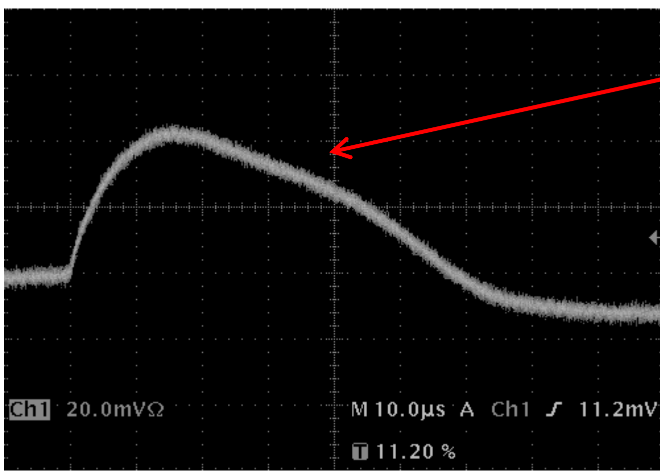
See: Further studies of cryogenic avalanche detectors based on GEMs, Bondar et al., Proceedings of Vienna Conf. on Instrum. 2004, NIM A (2004), in press.

He: signals induced by ions backdrifting in GEM3-GEM2 gap



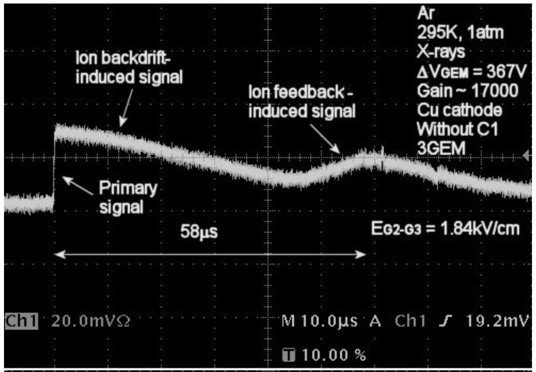
T = 295 K
*N=7.5*10^19 cm^-3*
Gain~30000
Cu cathode
Capacitor in GEM3up is on

Ion backdrift-induced signal



T = 295 K
*N=7.5*10^19 cm^-3*
Gain~30000
Cu cathode
Capacitor in GEM3up is off

Ar and He: signals induced by ions backdrifting in GEM3-GEM2 gap

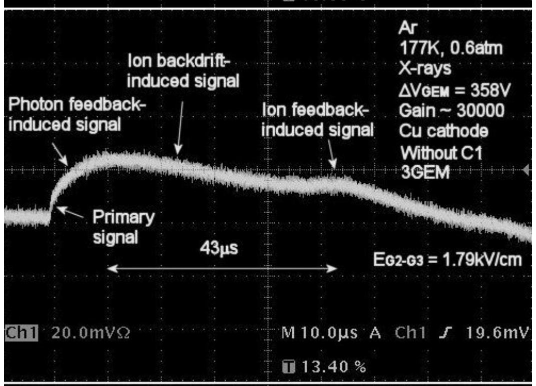


Ar, T = 295 K*, N=2.5*10^{19} cm^{-3} , Gain~17000, Cu cathode*

Capacitor in GEM3up is off

Estimated reduced ion mobility: ***K_0 = 1.7 cm^2/V s***

(Compare to 1.50 and 1.86 cm^2/V s for Ar^+ and Ar_2^+ respectively)

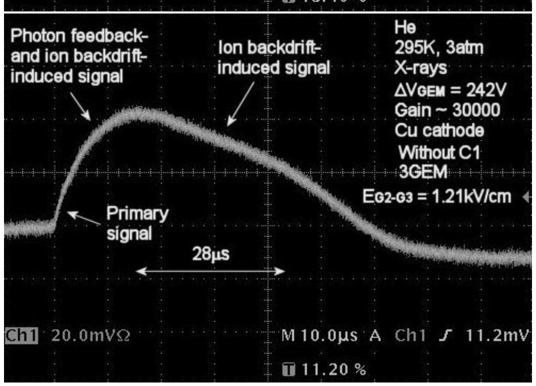


Ar, T = 177 K*, N=2.5*10^{19} cm^{-3} , Gain~30000, Cu cathode*

Capacitor in GEM3up is off

Estimated reduced ion mobility: ***K_0 = 2.4 cm^2/V s***

(Compare to 2.2 cm^2/V s obtained from 1/T$^{1/2}$ dependence)



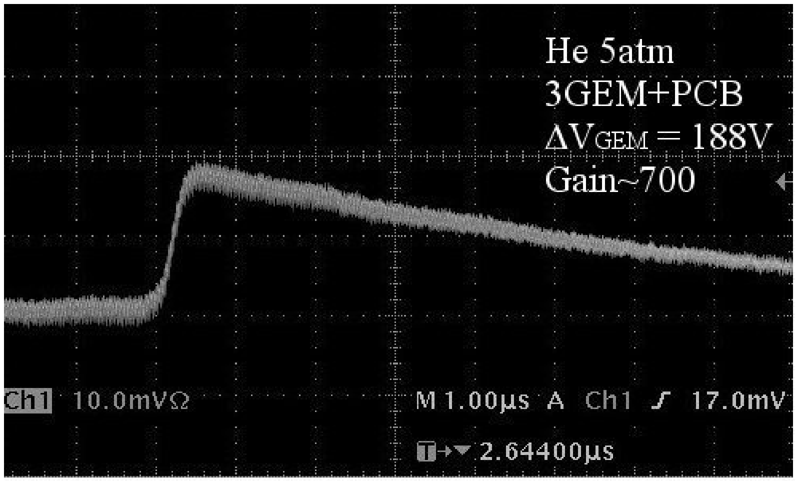
He, T = 295 K*, N=7.5*10^{19} cm^{-3} , Gain~30000, Cu cathode*

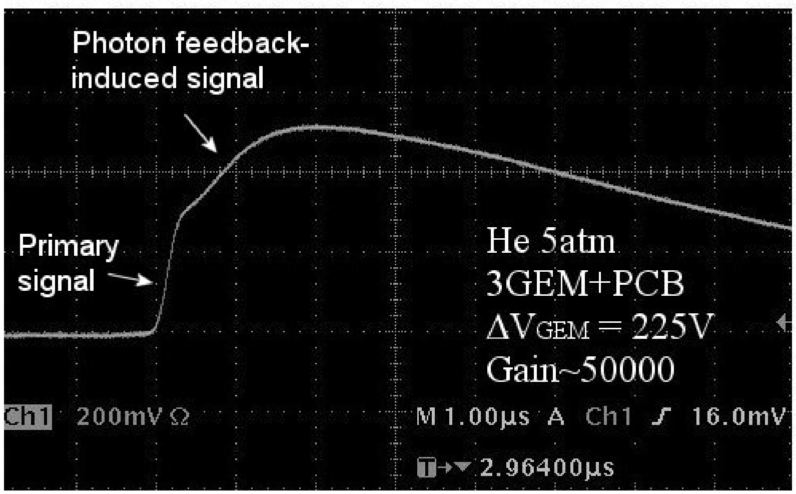
Capacitor in GEM3up is off

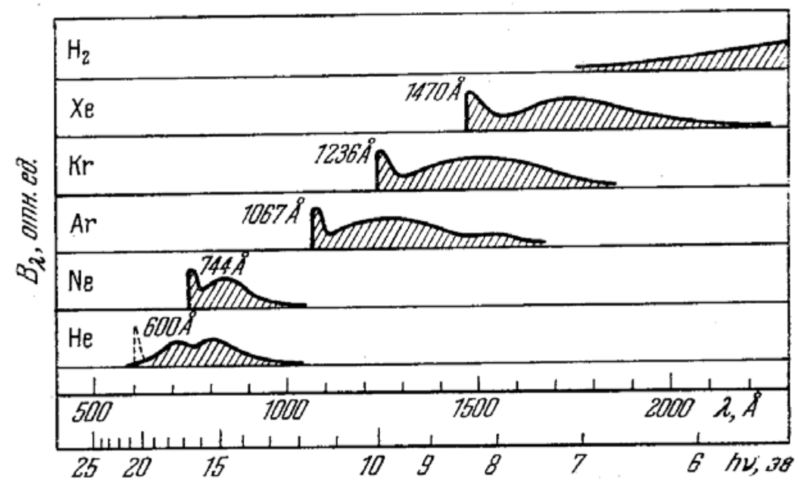
Estimated reduced ion mobility: ***K_0 = 16 cm^2/V s***

(Compare to 10.4 and 16.7 cm^2/V s for He^+ and He_2^+ respectively)

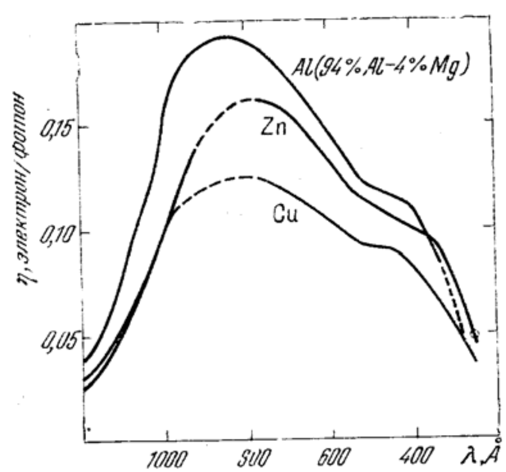
He: photon feedback at high gains, at room T and with Cu cathode





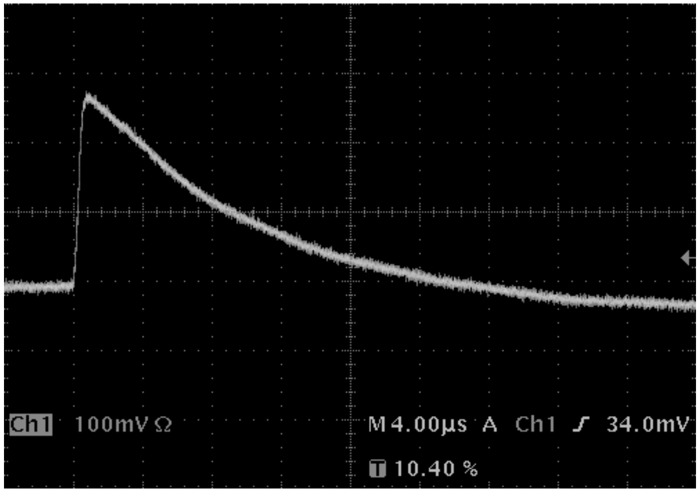


Emission spectra of noble gases.

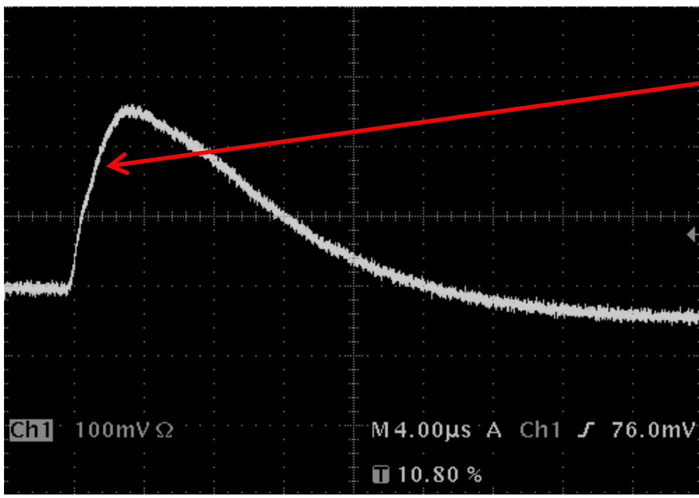


Quantum efficiency in VUV region.

He: photon feedback using Cu cathode



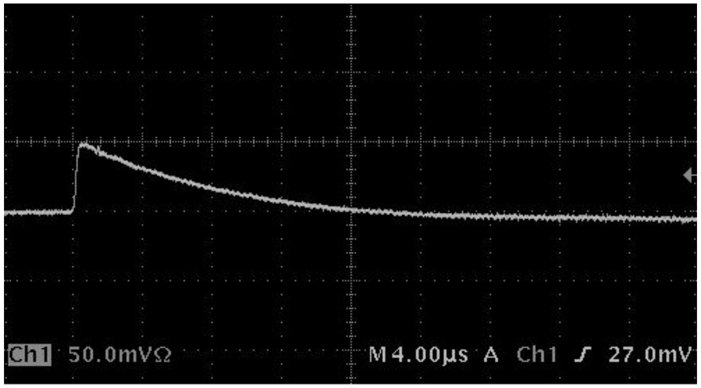
T = 124 K
*N=7.5*10^{19} cm^{-3}*
Gain~25000
Stainless steel cathode

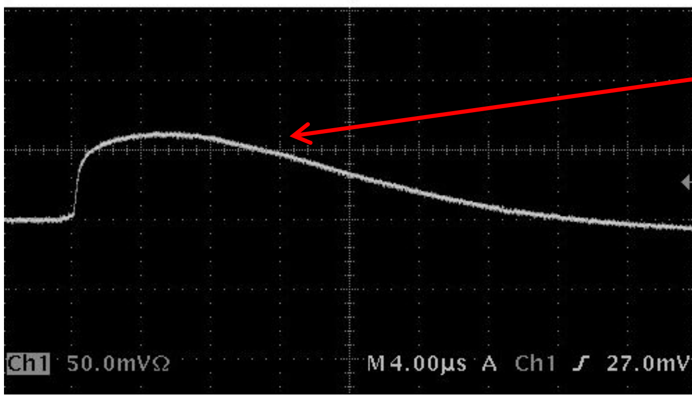


Photon feedback-induced signal

T = 295 K
*N=7.5*10^{19} cm^{-3}*
Gain~30000
Cu cathode

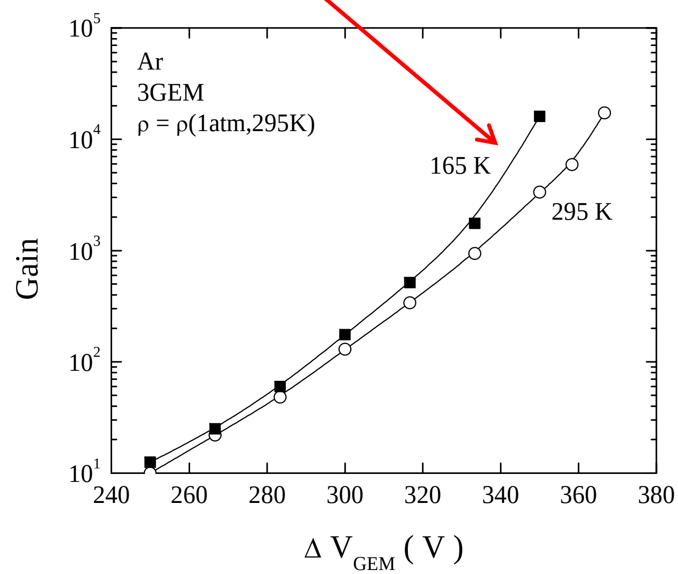
Ar: photon feedback enhancement at low T





T = 295 K
*p = 1 atm , N=2.5*10^19 cm^-3*
Gain~2000, V=2050 V
Cu cathode

T = 170 K
*p = 0.58 atm , N=2.5*10^19 cm^-3*
Gain~6000, V=2050 V
Cu cathode
Photon feedback



Conclusions

We have studied the performance of cryogenic avalanche detectors of ionizing radiation based on GEM multipliers and operated in gaseous and two-phase (liquid-gas) mode in pure He, Ar and Kr.

- ***It was shown that GEM structures could successfully operate at cryogenic T, down to 120 K, both in gaseous and two-phase modes.***
- ***High gas gains, exceeding 10^4, were obtained at cryogenic T in gaseous mode, in all noble gases studied. Electron avalanching at cryogenic T, in the range of 120-300 K, has either weak, in He, or moderate, in Ar and Kr, temperature dependence.***
- ***Stable avalanche mode of operation was observed in two-phase mode, in Kr at gains below 1000, indicating on possibility of long-term operation in avalanche mode in saturated vapor, using GEMs.***
- ***In two-phase mode, signals induced by X-rays and gamma-quanta and beta-particles were successfully recorded, in current and pulse-counting mode, respectively.***

Outlook: physics of CAD

Physics of electron avalanching at low T:
- *Ionization coefficients at low T*
- *Associative ionization at low T*
- *Avalanching in saturated vapor*
- *Electron and ion mobility at low T*

Physics of two-phase media:
- *Electron emission from liquid (solid) into gas phase*
- *Ion transport through phase interface*
- *Charging-up effects at phase interface*

Physics of ion clusters at low T:
- *Ion clustering*
- *Mobility of ion clusters*

Outlook: possible applications

- ***Two-phase* cryogenic *particle* and *X-ray* detectors: in He and Ne, for solar neutrino, and in Kr and Xe, for dark matter and PET/SPECT.**

- ***High-pressure X-ray* detectors in Xe and Kr, for mammography and radiography.**

- ***Neutron* detectors in *compressed* He^3, He acting as both a detection and amplification medium.**

- ***Sealed* detectors.**